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14. ABSTRACT

We show that various types of miniature semiconductor diodes floating in water act as self-propelling particles when powered by external alternating electric field. The millimeter-sized diodes rectify the voltage induced between their electrodes. The resulting electroosmotic force propels them in the direction of either the cathode or the anode depending on their surface charge. The motion of these rudimentary self-propelling micromachines can be controlled by internal logic. The semiconductor elements could emit light or respond to light, move at internally controlled speed and could be used as propellers for rotating freely-suspended "gears" and future autonomous micromachines. Diodes embedded into walls of microfluidic channels provide locally distributed pumping or mixing functions powered by a global external field. The combined application of AC and DC fields in such devices allows decoupling the velocity of the particles and the liquid and could be used for on-chip separations.

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Summary of Major Accomplishments

(1) A new technique for making self-propelling microdevices based on semiconductor diodes powered by external AC field was developed. The velocity of the particles does not depend strongly on their size; the mobility force could, in principle, be used to propel particles or devices on the microscale. The semiconductor elements could emit light or respond to light, move at internally controlled speed and could be used as propellers for rotating freely-suspended "gears". They form prototypes for microrobotic devices.

(2) New classes of distributed diode micropumps and micromixers remotely actuated by AC fields was developed and characterized. These diode micropumps can be used for very efficient particle and molecule separations on a chip. They could be powered remotely and allow a new level of complexity and improvement in the areas of microfluidics, sensing, on-chip biomolecule manipulation and separations, etc.

(3) This research project established the foundation of a new approach for design and operation of actively controlled nanofluidic-electronic chips for manipulating liquids, solutes and analytes at the nanoscale. It allows to design, fabricate and study active components, which will provide the building blocks for integrated lab-on-a-chip devices. The fluidic components and operational units could be monitored and controlled by an underlying integrated electronic microcircuit.

Publications

- S. T. Chang, V. N. Paunov, D. N. Petsev and O D. Velev, "Smart" Particles, Actuators and Microfluidic Pumps Based on Remotely Powered Miniature Diodes, *Nature Mat.*, in review (2006).
- S. T. Chang, V. N. Paunov, D. N. Petsev and O D. Velev, "Characterization of a New Class of Distributed Microfluidic Mixers," *Lab. Chip*, in preparation (2006).

Presentations at scientific conferences and invited seminars

- O. D. Velev et al., Remotely Powered "Smart" Particles, MEMS Actuators and Microfluidic Pumps Based on Miniature Semiconductor Diodes. MRS National Fall Meeting, Boston, December 2006. (*Invited*)
- O. D. Velev, On-chip droplet and particle manipulation by electric fields: Application in microbioassays and self-propelling devices. Department of Chemical Engineering, Rensselaer Polytechnic Institute, VA, March 2006. (*Invited seminar*)
- O. D. Velev et al., Electroosmotic self-propelling particles and distributed microfluidic pumps based on miniature semiconductor diodes. 80th ACS Colloid and Surface Science Symposium, Boulder, CO, June 2006.

- O. D. Velev, On-chip droplet and particle manipulation by electric fields: Application in microbioassays and cell collection and assembly, Sandia National Laboratory, Livermore, CA, April 2006. (*Invited seminar*)
- O. D. Velev, On-chip droplet and particle manipulation by electric fields: Application in microbioassays and self-propelling devices. Department of Materials Science, Massachusetts Institute of Technology, Boston, MA, March 2006. (*Invited seminar*)
- O. D. Velev, On-chip droplet and particle manipulation by electric fields: Application in microbioassays and self-propelling devices. Department of Chemical Engineering, Virginia Tech., Blacksburg, VA, March 2006. (*Invited seminar*)
- O. D. Velev et al., On-chip manipulation by electric fields: From self-assembling particles to self-propelling devices, MRS National Spring Meeting; San Francisco, CA, April 2005. (*Invited*)

New discoveries, inventions, or patent disclosures

"Autonomous Self-Propelling Microcircuit Particles," Invention disclosure field with NCSU intellectual property office, 2005.

Technology importance and technology transfer

We have evaluated the potential technologies, including microrobotic prototypes, microfluidic devices and self-assembled biocircuits. Discussions will be carried out for developing practical high-technology devices with our collaborators at AFRL and industrial collaborators.

Personnel Supported

Two NCSU graduate students, Suk Tai Chang and Shalini Gupta have been supported for the full or part of the duration of this project.

"Smart" Particles, Actuators and Microfluidic Pumps Based on Remotely Powered Miniature Diodes

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Abstract

Microsensors and micromachines capable of self-propulsion through fluids could revolutionize many aspects of technology. Few principles to propel such devices and supply them with energy are known. Here we show that various types of miniature semiconductor diodes floating in water act as self-propelling particles when powered by external alternating electric field. The millimeter-sized diodes rectify the voltage induced between their electrodes. The resulting particle-localized electroosmotic flow propels them in the direction of either the cathode or the anode, depending on their surface charge. These rudimentary self-propelling devices can emit light or respond to light and could be controlled by internal logic. Diodes embedded into walls of microfluidic channels provide locally distributed pumping or mixing functions powered by a global external field. The combined application of AC and DC fields in such devices allows decoupling the velocity of the particles and the liquid and could be used for on-chip separations.

It is not easy to make small particles and devices that propel themselves in liquid. Viscous effects predominate on the microscale and render most mechanical means of propulsion inefficient[1-4]. The flagellar and ciliar bacterial motors are among the few natural chemical-mechanical ways of propelling on the microscale[5-8]. Significant progress has been achieved in the synthesis of artificial molecular machines including molecular motors[9,10], shuttles[11], and "nanocars"[12]. Such molecular machines can in principle propel microdevices or act as micropumps when attached to walls[13,14], but it is hard to adapt these complex natural or artificial molecular structures to engineered devices[15]. A couple of notable studies report bimetal particles propelling via catalytic decomposition of solutions of hydrogen peroxide[16,17]. A few other papers discuss the undulatory motion of polymer gel under electric field[18,19], a swimming screw machine driven by an external magnetic field[20], a camphor boat with ester vapor as a chemical stimulus[21], biomimetic swimming robots inspired by *E. coli* motility[22], a carbon-fiber-based bioelectrochemical motor driven by oxidation of glucose[23], and 'microoxen' cells moving microscale loads[24]. Some of these particles, however, only move in special media, while others cannot be scaled to microscopic dimensions.

We demonstrate here how various semiconductor diodes form a new class of self-propelling "particles" and pumps in microfluidic devices. External energy is provided by a global external AC electric field. DC voltage is induced between the electrodes of each diode as a result of rectification of the AC field. The constant electric field between the electrodes leads to electroosmotic flow, which may propel the diodes or pump the adjacent liquid (Fig. 1). In effect, the semiconductor microelements harvest electric energy from external AC fields and convert it into mechanical propulsion on the microscale.

Two types of experiments were performed in order to demonstrate how the flow of the adjacent liquid generated by the diodes can be used in microdevices. First, we studied how semiconductor diodes floating on the surface of water and aqueous solutions can self-propel directionally. The devices used included a range of regular (switching) diodes and diodes with additional functionality - light emitting diodes (LED), photodiodes and Zener diodes (for specifications see the Supplementary Information). Their sizes ranged from 1-millimeter microdiodes to regular diodes a few millimeters long. The diodes floated suspended by the interfacial tension on the surface of water contained in a wide Petri dish. AC fields of square wave form, frequency 10 Hz - 37 kHz and magnitude 30-150 V/cm were applied across the water by a pair of wire electrodes dipped at the sides of the container (Fig. 1).

The application of alternating electric fields did not lead to any perceptible liquid motion in the vessel or bubble formation at the thin wire electrodes. The field was spatially uniform and there were no dielectrophoretic forces[25-27] (other than torque) acting on the particles. The diodes suspended on the liquid surface first became oriented in the direction of the field lines

(perpendicular to the electrodes) when the field was turned on. The microelements then began to move parallel to the electric field, always in one direction only with regards to the orientation of their anode and cathode (Fig. 2a,b). Velocities as high as millimeters per second were observed. Movies illustrating diode motion are provided in Movies M1-M3. The diodes were propelled with approximately constant velocity until reaching the opposite electrode and then stopped a few millimeters in front and above the electrode where the intensity of the field decreases. If the diodes were then rotated manually in the opposite direction they moved with the same constant velocity until reaching the vicinity of the other electrode.

We proved that the diode motility results from a local electroosmotic flux powered by the external field. The specific direction of motion with regards to the diode cathode and anode points out that a DC field along the diode is responsible for its mobility. The origin of this DC field can be understood by analyzing the equivalent electric circuit of the experimental system, shown at the bottom of Figure 1. The electric voltage induced in the diode by the external field can be estimated from a model including resistors describing the ionic conductance through the bulk liquid and capacitors for the ionic layers. At the low frequencies used in this study the resistance is likely to be the leading contribution. The diode short-circuits the negative half-periods of the AC current. The resulting DC voltage of magnitude V_d induced in the diode can be approximated as

$$V_d = \frac{1}{2}\frac{R_2}{(R_1 + R_2 + R_3)} V_{ext} \tag{1}$$

where V_{ext} is the AC peak-to-peak voltage applied to the electrodes in the dish and R_1-R_3 are defined in Figure 1. The coefficient of ½ accounts for the two-fold decrease of the voltage during the rectification of AC into DC. Assuming that the resistance of the liquid is linearly proportional to the distance between the electrodes, after expressing the external field intensity and substituting in equation (1), we arrive at the simple formula $V_d = E_{ext}\, l_d/2$, where l_d is the length of the diode body and E_{ext} is the external AC field. Commercial semiconductor diodes have an offset voltage in the forward direction, which is an intrinsic property of the *pn* junction[28]. In a real system this offset voltage has to be compensated for by an additional field of E_{d0}. Thus the above equation applied to real diodes reads:

$$V_d = \frac{l_d}{2}(E_{ext} - E_{d0}) \tag{2}$$

We measured the voltage generated across diodes dipped in the vessel as a function of the external field and distance between electrodes and found good quantitative agreement with this formula.

The DC field rectified between the electrodes gives rise to electroosmotic fluid flow along the plastic body of the diodes. This electroosmotic effect is analogous to the one used to

pump liquids in microfluidic devices[29,30], however, it originates here at an electronic device converting locally the energy of the external field into flow. The electroosmotic flow pushes reactively the diodes in the opposite direction (see top portion of Fig. 1). The velocity of the electrokinetic flux u_w induced by the tangential DC field between the diode electrodes, E_w, can be estimated by the Helmholtz-Smoluchowski equation[31]

$$u_w = -\frac{\varepsilon \varepsilon_0 \zeta}{\mu} E_w \tag{3}$$

where ε and ε_0 are the dielectric permittivity of the media and vacuum, respectively, μ is the viscosity of the liquid phase and ζ is the potential in the plane of hydrodynamic shear[31]. The velocity, u, of a particle floating on a free liquid interface is likely to be different than that of a completely submerged particle, so we add a hydrodynamic resistance correction coefficient β in the equation: $u = -\beta u_w$. The electric field along the diode wall is $E_w = V_d / l_d$. Substituting these relations in equation (3) we obtain a formula estimating the diode velocity as a function of the intensity of the external AC field

$$u = \beta \frac{\varepsilon \varepsilon_0 \zeta}{2 \mu} (E_{ext} - E_{d0}) \tag{4}$$

Notably, equations (3) and (4) differ not only in the coefficients, but in the type of electric field, DC in equation (3) and AC in equation (4). An intuitive way of presenting equation (4) is that a diode subjected to an external AC field will "short-circuit" all half-periods of the field in the direction in which the diode is conductive; the remaining "rectified" half-periods will generate electroosmotic flux, which in turn will propel the diode. This formula demonstrates that the self-propelling effect reported here *does not depend on the diode size*, which cancels out of the expressions (provided that $E_{ext} >> E_{d0}$ or that E_{d0} scales down with diode size). A microscopic diode-based device could move about as fast as a macrosized diode. We verified this simple model by experiments where the velocities of a 1-mm sized microdiode and a regular 3.7-mm diode were measured as a function of the applied voltage (Fig. 3a). The velocities of both diodes were approximately equal (the average velocity of the microdiode actually was a little higher at lower fields, possibly due to the lower hydrodynamic drag). After substituting the value of E_{d0} measured experimentally in the static diode experiments, and assuming a typical value of $\zeta = 80$ mV, we fitted these data by equation (4) with the only fitting parameter of $\beta = 3.0$. This is a reasonable value for the coefficient of hydrodynamic resistance β as the diode moves onto a free liquid surface and where the resistance is likely to be smaller than for a fully immersed particle. Verifying equation (4) for smaller diodes is presently difficult due to the lack of commercial devices of such size, however, alternative fabrication techniques[32,33] might allow in

the future to test the technique with much smaller diodes and investigate the effects of Brownian motion and counterionic atmosphere in the Hükel regime[31].

The electroosmotic nature of the phenomena was proven by a variety of experiments. The ζ-potential of the plastic diode surface is a function of pH, electrolyte concentration, and presence of charged surface-active species. We examined the effect of varying concentrations of acids, bases, charged surfactants, and electrolytes on the diode mobility (Fig. 3b and Supplementary Figs. S2, S3). The strongest effect is observed when pH is increased by adding NaOH or Na_2HPO_4. The mobility of the diode first decreases and then changes direction (i.e., instead of moving in the direction of their anode the diodes begin propelling with the cathode side in front). This can be attributed to re-charging of the diode surface at higher pH. Indeed, when these data are plotted in coordinates of velocity vs. pH (Fig. 3b), they overlap, indicating an isoelectric point of the diode polymer surface at pH ≈ 6.4. Negatively charged surfactant, sodium dodecyl sulphate, first suppressed the mobility of the diodes and then reversed their direction. Positively charged surfactant, cetyl trimethyl ammonium chloride, on the other hand increased the diode mobility. Such effects are common in electroosmosis and can be explained by change of the intrinsic charge of the surface because of surfactant adsorption[31]. These changes in diode motion direction and velocity suggests a potential for sensing functions based on surface functionality. The effect of electrolyte was also typical for electroosmotic-driven flows, as the velocity remained approximately constant at small electrolyte concentrations, while bubbling and electrochemical flows emerged at higher electrolyte concentrations (Supplementary Figure S3). We also established that the diodes self-propel in non-aqueous media such as ethylene glycol and dimethyl sulfoxide.

Finally, we characterized the diode velocity in water as a function of the frequency of the external electric field (Fig. 3c). We found no correlation between these two parameters within the frequency range of 10 Hz to 37 kHz. This result proves that the contribution of AC electrokinetic effects is negligibly small, as AC electrokinetics[25,34-40], arising from ionic mobility in electric field gradients, is strongly dependent on the field frequency. It also points out that the diodes could be powered with fields in the radio (RF) or even microwave frequency range. Prototypes of small, inexpensive, yet complex, microcircuits powered remotely by external RF fields already exist in the form of radio frequency identification (RFID) microchips. Self-propelling diodes, powered remotely, may form the basis of a new class of microdevices of unprecedented complexity. We demonstrated rudimentary examples of a range of functionalities by using different types of commercial diodes (Table 1).

Table 1.
Types of semiconductor elements used and functionality demonstrated.

Type of diode	Mobility specifics	Principle demonstrated
Regular switching	Moves with velocity $u \sim E_{ext}$	Electrohydrodynamic propulsion (Fig. 2a)
Light-emitting (LED)	Moves and emits light	Double functionality, propulsion and light emitting (Fig. 2b)
Zener	Moves at an approximately constant velocity above a certain E_{ext}	Internal electronic control of motility (Fig. 3d)
Photodiode	Movement stops when illuminated with strong light source	External control of motility by light (Movie M6)

The voltage rectified between the diode electrodes can also be used to power additional functions of the electronic microcircuits. For example, light emitting diodes (LEDs) suspended in the experimental vessel ***both*** propelled themselves electroosmotically and emitted light (Fig. 2b, Movies M3 and M5), demonstrating that the DC voltage rectified between the electrodes can power additional device functions. A rudimentary control of the velocity by a pre-programmed function of the semiconductor element was achieved by using Zener diodes, which stabilize the reverse voltage on their *pn* junction at a certain threshold value[28]. Indeed, the electroosmotic velocity of Zener diodes remained approximately constant above the corresponding value of the external voltage (Fig. 3d). Moving diodes can respond to external stimuli or signals, which was demonstrated by the use of photodiodes whose velocity could be controlled by light (see Movie M6). The particle-localized electrohydrodynamic effect described here can also be used in diode-actuated electroosmotic motors and actuators. This was illustrated by constructing "gears" powered by a ring of regular switching diodes or by LEDs converting the energy of the external field into rotational motion. (Fig. 2c and Movies M4 & M5).

The electroosmotic flux of the liquid generated between the diode electrodes can also be used to pump liquids on the microscale, if the diodes are immobilized. In the second cycle of experiments we proved that the diodes can operate as distributed, locally operating, micropumps in microfluidic devices. The test microfluidic device constructed to evaluate the diode pumping action is schematically shown in the bottom half of Figure 1. It was based on a closed rectangular channel 600 μm wide and 570 μm high and of overall dimensions of 20 mm×5 mm. The AC

field was applied to two electrodes situated symmetrically in the opposing short sections of the channel. Because of the symmetry of the channel and electrode placement, neither AC nor DC fields applied to the electrodes could engender macroscopic liquid circulation. The pumping was performed by two diodes embedded in the opposing walls of the channel and oriented in the same direction. The liquid flow was observed with the help with fluorescent tracer particles. When an AC field was applied to the electrodes, macroscopic circulation of the liquid around the channel was observed as a result of the local electroosmotic flow driven by the diodes. At the same time, intense movement of the liquid in the direction of the macroscopic flow and a backflow in the middle of the channel were observed between the diode surfaces (Fig. 4a). The dependence of the microscopic velocity (measured in the channel without diodes) on the AC voltage applied (Fig. 4c) was similar to the velocity of diode propulsion (cf. Fig. 4c with Fig. 3a). Theoretical calculations of the macroscopic flux and computer simulations of the flow pattern in between the diodes were in excellent agreement with the experimental data and will be published elsewhere. Instead of pumping the liquid, the two diodes in the channel wall could act as a microfluidic mixer when facing in opposite directions and creating a circular flow inside the channel (Fig. 4b).

A major advantage of this method is the ability to position multiple micropumps and mixers in different locations on the chip and power all of them with a global AC field (or RF waves) applied to the whole device. The AC field driven pumps open unique opportunities in microfluidics when combined with DC electrophoresis and DC electroosmosis. One example is the ability to decouple the electrophoretic mobility of a particle or a biomolecule from the flow of the surrounding liquid. The difference in the charge and electrophoretic mobility is the major factor of separation of proteins, polynucleotides, cells and particles in microfluidic devices[41-45]. The particles are separated in external DC field. Typically, however, the surrounding liquid also moves by electroosmosis and particles with small differences in electrophoretic mobility might not be separated during the time they are transported through the channel[45]. The diode pumps, however, are actuated by AC fields, which do not affect the electrophoretic mobility of the particles outside of the diode location. The velocity of a particle, V_{particle}, will be the sum of the electrophoretic and liquid velocities

$$V_{\text{particle}} = V_{\text{eph}}(E_{\text{DC}}) + V_{\text{liquid}}(E_{\text{AC}})$$

The DC and the AC components of the field *can be applied simultaneously, but controlled independently*. The AC field controls the liquid flow from the diode pump, while the DC field controls the electrophoretic particle velocity. If the AC-induced liquid flow is in a direction opposite to the one of the particles, they could be moved either in the positive direction, when $|V_{\text{eph}}| < |V_{\text{liquid}}|$, or in the negative one, when $|V_{\text{eph}}| > |V_{\text{liquid}}|$. For each value of the DC

component there is a value of the AC field where the electrophoretic mobility will be fully compensated by the diode-generated counterflux, so each type of particle in a mixture can be held in place by a dynamic equilibrium and separated from the others. By precisely adjusting the DC and AC components, particles with small differences in charges or size can be separated more efficiently than by electrophoresis alone. The ability to drive the diode pumps at frequencies exceeding 10 kHz could eliminate problems with fluid flows and vortices in areas of non-uniform field that may occur in microfluidic pumping by conventional AC electrohydrodynamics[36-40].

We proved the above separation concept by experiments with a mixture of two types of negatively charged particles. The velocities of each particle type in the long channel (without the diodes) as a function of the DC and AC components of the field are plotted in Figure 5. The principle of the technique can be illustrated by considering, e.g., the velocity of the two types of particles at DC = 6 V/cm and AC = 60 V/cm (Fig. 5). The two particles *move in different directions, even though they carry charges of the same sign.* This process is illustrated in the Movie M7. Such microfluidic processes conveniently controlled by two electrical parameters can lead to highly precise particle, cell and biomolecule separations and characterizations on a chip.

In summary, we demonstrate that semiconductor diodes submerged in water interact with external AC fields and generate directional electroosmotic flux that can propel them or pump liquid on the microscale. The power can be provided by AC electric fields of high frequencies potentially spanning the radio frequency and microwave regions. The DC voltage rectified across the diodes can be used to power microcircuits encased in the microdevices. Semiconductor elements (diodes in this study and more complex devices in the future) may not only be used in electric circuits, but also might serve as building blocks of new classes of functional materials and devices. The electroosmotic propellency may be used in dynamically reconfigurable microfluidic chips, spatially-evolving active microsensor networks, or possibly in future complex motile devices such as microbots for medical diagnostics and surgery.

Methods

The experiments except diode "gear" were carried out in a plastic Petri dish of dimensions 9 cm × 9 cm × 1.5 cm in depth. A couple of thin wire electrodes were submerged on the top and bottom of the vessel with 7 cm distance, providing uniform electric field across the liquid. The experiments of the diode "gear" were carried out in a vessel of dimensions 8 cm × 4 cm × 1 cm in depth with a 3.5 cm gap between the thin wire electrodes. The signal to the electrodes was provided by an AC generator (FG-7002C, EZ Digital Co. Ltd., Korea) and amplifier (PZD 700, Trek, Inc., Medina, NY, USA), and was monitored with oscilloscope and digital voltmeter. The smaller diodes were floated directly on the surface of water suspended by the interfacial tension.

Small floaters made of silicon glue were attached to the side of the larger switching diodes. The diode positions were observed with an Olympus SZ61 stereomicroscope and recorded with the attached Sony DSC-V1 digital camera.

The microfluidic chips were fabricated from poly(dimethylsiloxane) (PDMS) using soft lithography. The rectangular channel master from SU-8 photoresist (MicroChem Co., Newton, MA, USA) was fabricated on a silicon wafer. Two silicon switching diodes were attached on the side wall of the master at the center of the longer channel using a 500 μm thick sticky rubber patch. The PDMS (Sylgard 184, Dow Corining, Midland, MI, USA) was cast on the master with the attached diodes and cured at 70 °C. The PDMS replica with the embedded diodes was irreversibly sealed to a PDMS film coated on the glass slide using air-plasma cleaner (Model PDC-32G, Harrick Plasma, Ithaca, NY, USA). The particles used in the microfluidic experiments included fluorescent 1 μm amidine-stabilized polystyrene latex from Interfacial Dynamics Co. (Portland, OR, USA) and fluorescent 2 μm sulfate-stabilized polystyrene latex from Molecular Probes (Eugene, OR, USA). The diode pumping was characterized with a dispersion of 0.002 wt% 2 μm fluorescent latex in deionized (DI) water at pH ~ 5.04 containing also 10^{-4} wt% Tween-20 and 10^{-5} M NaCl. The dispersions for the decoupling experiments contained 0.0002 wt% of amidine- and sulfate-stabilized latex particles each in pH ~ 7.0 DI water with 10^{-4} wt% Tween-20 and 10^{-5} M NaCl. The particle zeta-potentials at this pH measured by electrophoretic light scattering were -72.7 mV and -131 mV correspondingly. The suspensions were injected into the channel through two syringe needles inserted in the short channel sections. The external AC and DC electric fields were applied through the needles by using the generator in DC-offset mode. The motion of particles was monitored using Olympus BX-61 microscope in reflection and fluorescent mode microscopy.

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Figures and figure captions

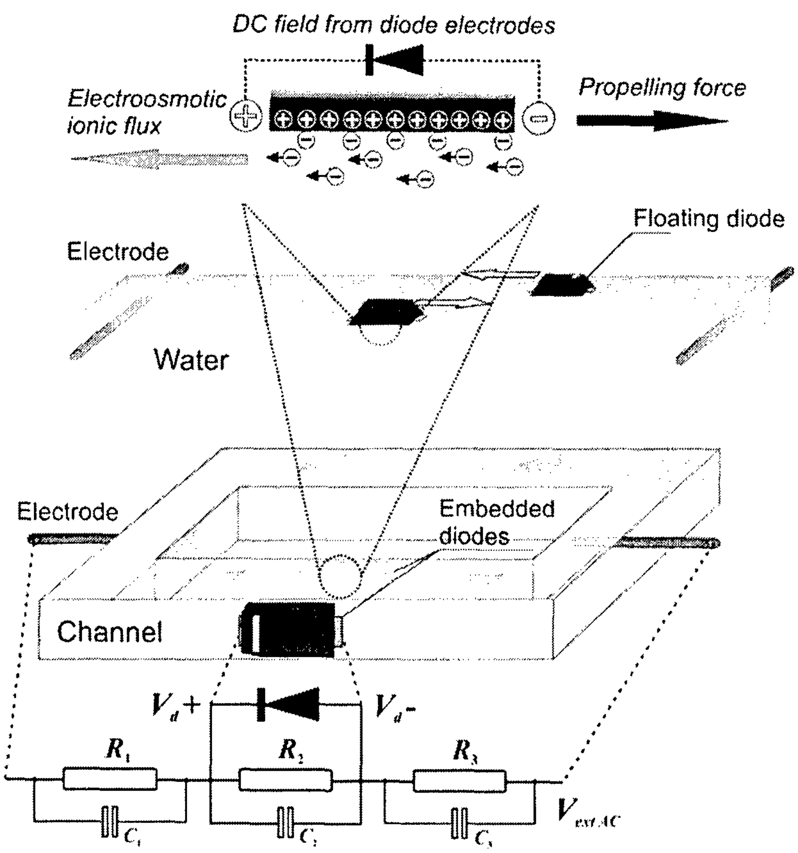

Figure 1. Schematics of the experiments for measuring floating diode velocity and diode pumping rate in a model microfluidic device. The origin of the localized electroosmotic flow and the equivalent electric circuit used to analyze the magnitude of the DC voltage V_d induced in the diode are shown in the top and bottom respectively.

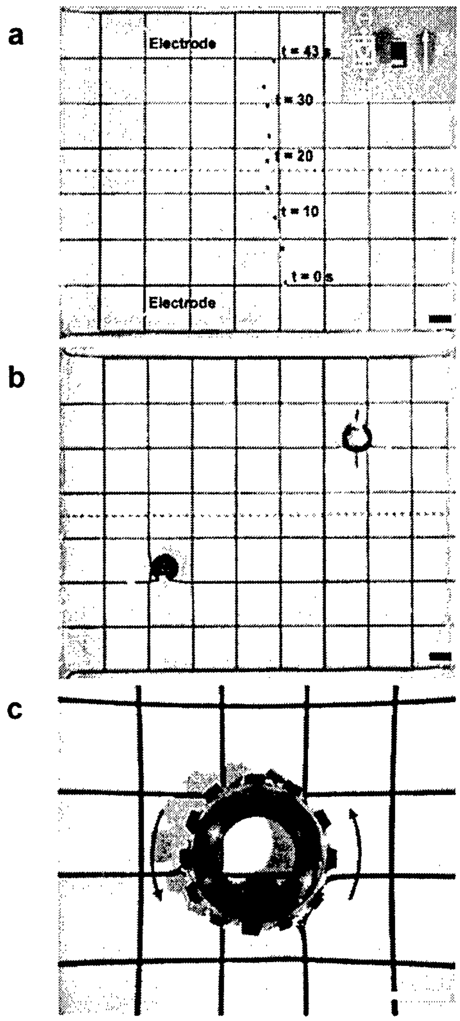

Figure 2. Optical micrographs of self-propelling semiconductor "particles": (a) Overlay of a series of photographs at low magnification showing the 5 cm directional "voyage" of a propelling microdiode (seen here as small black rectangle) for a total duration of 43 s (see also Movie M2). (b) Two LEDs light up and move towards the top or bottom depending on the orientation of their anodes (marked white). This experiment demonstrates the potential of diode-based devices to deliver additional functionality based on the voltage induced between their electrodes (see also Suppl. Movie M3). (c) Use of diodes as propellers and actuators in MEMS - a rotor ring with diodes attached to its periphery spins around when an external field is applied (see also Movie M4). All experiments in (a), (b), (c) were performed at external voltage, E_{ext} = 120 V/cm, frequency 1 kHz, and 10^{-6} M NaCl. Scale bars = 5 mm.

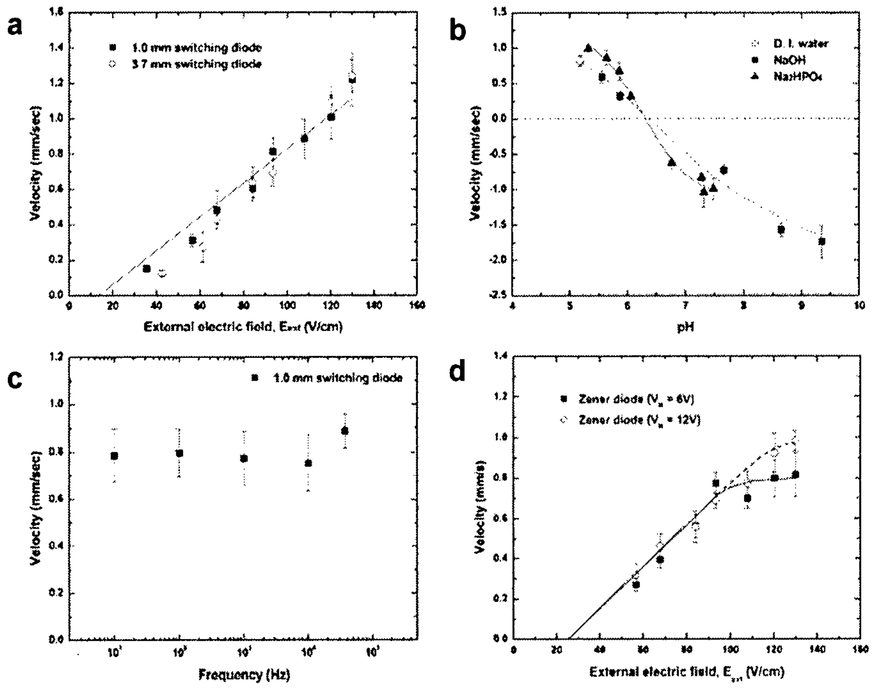

Figure 3. Dependence of the diode velocity on parameters controlling the electroosmotic propellant force: (a) Velocity as a function of the external AC field. The line is plotted on the basis of equation (4) with only one fitting parameter, $\beta = 3.0$. Note that the velocity of the diodes is similar even though there is almost 4-fold difference in their size. (b) Diode velocity as a function of pH. The direction of the motion changes at a pH = 6.4, as the surface charge of the resin body changes sign at the isoelectric point. (c) Diode velocity is not a function of the frequency of the external field up to frequencies in the RF region. (d) When Zener diodes are used instead of switching diode the maximal velocity is restricted as a function of the characteristic reverse voltage of the Zener element. The curves are guides to the eye. Experiments (a), (b) and (d) were performed at 1 kHz. 10^{-6} M NaCl solution was used in (a), (c) and (d). Experiments (b) and (c) were performed at $E_{ext} = 93$ V/cm.

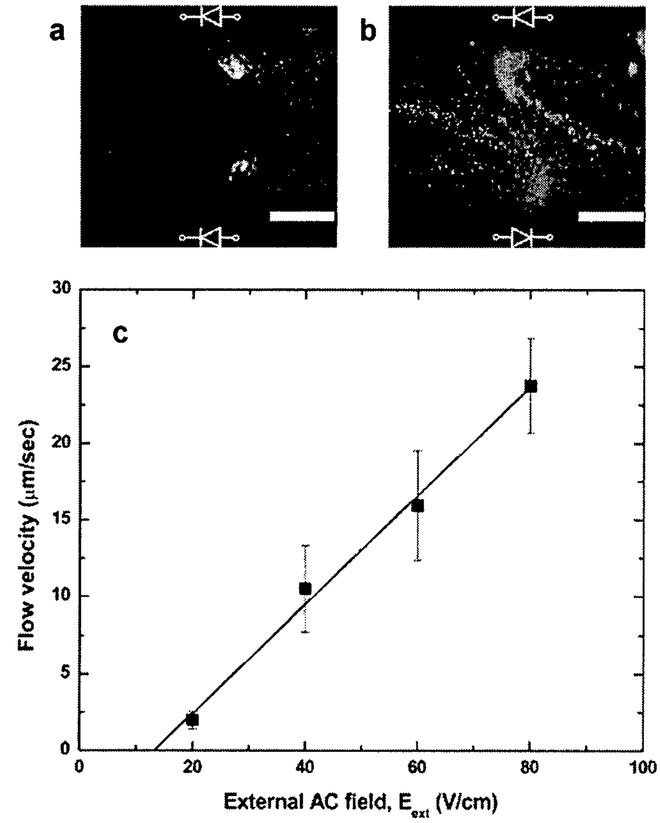

Figure 4. Flow of particle suspension in a microfluidic channel generated by two diodes embedded in the top and bottom sides of the channel, as observed from above. (a) Optical micrograph illustrating pumping and backflow for diodes with the same orientation. The diodes create a unidirectional flow by moving the liquid adjacent to the wall in same direction. (b) Micrograph illustrating the flow generated by two diodes with opposite orientation. The diodes create a circular flow by moving the liquid adjacent to the wall in opposite directions, which can be used for microfluidic mixing. (c) Velocity of the liquid pumped at the center of the long channel without diodes (circulating through the microfluidic loop) as a function of the external AC field - cf. with eq. (4) and Fig. 3a. Scale bars = 200 μm.

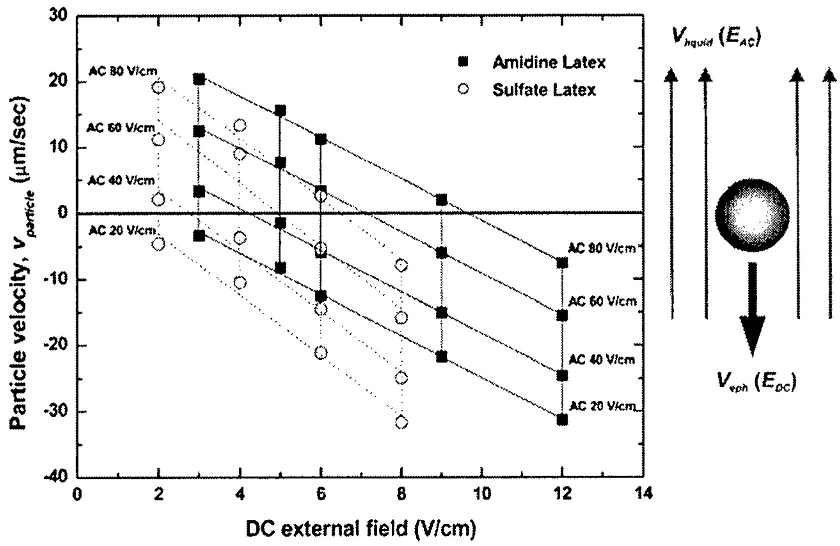

Figure 5. Particle velocities at the center of the long channel without diodes as a function of the magnitude of the AC and DC components of the external field. The direction of the AC and DC driven effects is shown to the right. The AC-driven diode pumps move the liquid in the positive direction. The increase of the DC component increases the (negative) electrophoretic velocity of the particles. At precisely adjusted values of the DC and AC fields near the position of dynamic equilibrium particles with small differences in surface charge can be separated efficiently (see also Movie M7).